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# Design of optimum criterion for opportunistic multi-hop routing in cognitive radio networks

**Ahmad Yousofi**[1] | **Masoud Sabaei**[2] | **Mehdi Hosseinzadeh**[3,4]

[1]Department of Computer Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.

[2]Department of Computer Engineering and Information Technology, Amirkabir University of Technology, Tehran, Iran.

[3]Department of Computer Science, University of Human Development, Sulaimaniyah, Iraq.

[4]Iran University of Medical Sciences, Tehran, Iran.

**Correspondence**
Masoud Sabaei, Department of Computer Engineering and Information Technology, Amirkabir University of Technology, Tehran, Iran.
Email: sabaei@aut.ac.ir

The instability of operational channels on cognitive radio networks (CRNs), which is due to the stochastic behavior of primary users (PUs), has increased the complexity of the design of the optimal routing criterion (ORC) in CRNs. The exploitation of available opportunities in CRNs, such as the channel diversity, as well as alternative routes provided by the intermediate nodes belonging to routes (internal backup routes) in the route-cost (or weight) determination, complicate the ORC design. In this paper, to cover the channel diversity, the CRN is modeled as a multigraph in which the weight of each edge is determined according to the behavior of PU senders and the protection of PU receivers. Then, an ORC for CRNs, which is referred to as the stability probability of communication between the source node and the destination node (SPC_SD), is proposed. SPC_SD, which is based on the obtained model, internal backup routes, and probability theory, calculates the precise probability of communication stability between the source and destination. The performance evaluation is conducted using simulations, and the results show that the end-to-end performance improved significantly.

**KEYWORDS**
backup routes, channel diversity, cognitive radio network, routing criterion

## 1 | INTRODUCTION

Recent studies on the use of the radio spectrum (RS) have shown that static spectrum management has resulted in a failure to maximize the exploitation of this scarce and valuable resource [1]. The exponential growth of new services that require access to RS [2] (such as road networks [3] and mobile social networks [4], etc.) and which increase congestion in the unlicensed bands [5] have resulted in the impression that there is a physical scarcity of RS. To overcome these difficulties, the policy of dynamic spectrum access enables users to be divided into two groups: primary or licensed users (PUs), and secondary or unlicensed users (SUs)[1)] [1]. In this policy, PUs have a higher priority with respect to RS use. SUs can instead find spectral holes[2)] using a cognitive radio equipment, and can use them in an opportunistic manner to send the data without causing disturbance to PUs. The use of this policy in wireless transmission environments has led to the development of cognitive radio networks (CRNs) [6]. CRNs can be used in various fields such as disaster management, emergency and public safety communications, and urban area planning.

In the CRN implementation, the changes in different layers of the network protocol stack have produced various types of issues and problems [7–12]. One of the most important issues is the routing criterion definition.

[1)]SUs are also known as cognitive users (CUs).

[2)]The spectral hole is the period of time for which a PU does not use its channel.

Many factors are related to CRN routing, and it impossible to consider all of them when defining the routing criterion [13,14]. Consequently, the definition of the optimal routing criterion in CRNs has become a challenging and interesting issue for researchers [15,16].

In CRNs, the aim is to determine the route with the greatest stability and least disturbance for the PU receivers. Therefore, the behavior of PU senders and the protection of PU receivers are fundamental factors in route-weight calculations.

Usually, there are multiple channels between neighboring SUs in CRNs (channel diversity). Moreover, other routes may exist through intermediate nodes belonging to the route in order to reach the destination node (internal backup routes). The next section illustrates the effects of these two factors on the route-weight calculation.

In Figure 1, without channel diversity, only channel 1 or channel 2 can be used to establish communication between $SU_s$ and $SU_d$, where s is the number of source node and d is the number of destination node. In this case, if $PU_5$ to $PU_{10}$ are inactive, the activity of $PU_1$ and $PU_3$ (if channel 1 is used) and the activity of $PU_2$ and $PU_4$ (if channel 2 is used) cause a disconnection in the communication between SUs and $SU_d$. However, considering the channel diversity, if $PU_5$ to $PU_{10}$ are inactive, the communication remains stable between $SU_s$ and $SU_d$.

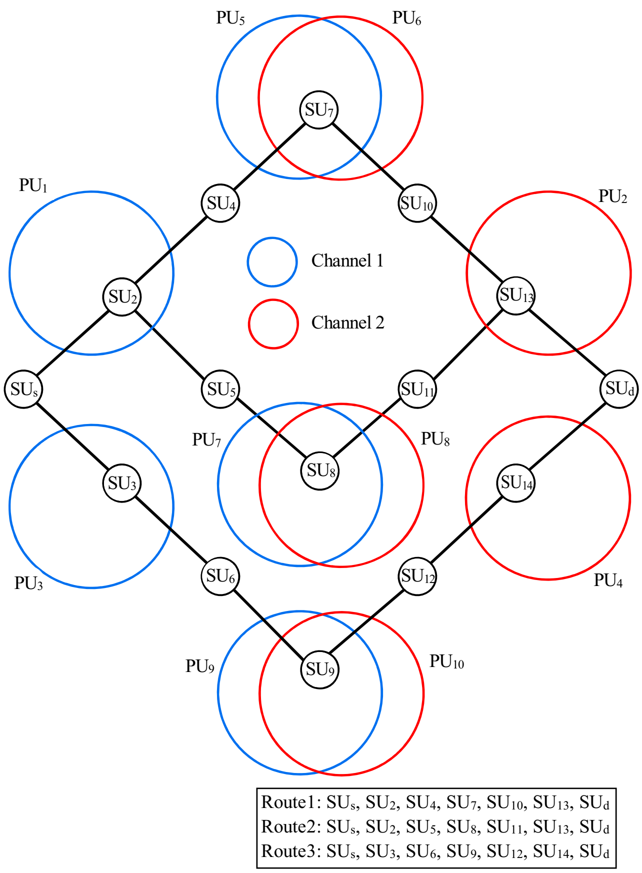


**FIGURE 1** Effect of the channel diversity and internal backup routes on the routing. The activity probability of primary users (PUs), the average duration of activity of PUs, and the delay of the links are equal. The odd-indexed PUs and even-indexed PUs act on channels 1 and 2, respectively

Figure 1 clearly illustrates that either Route 1 or Route 2 is the best route to send data from $SU_s$ to $SU_d$ because a part of Route 2 is the internal backup route for Route 1, and vice versa. Nevertheless, if the internal backup routes are overlooked, the stability probability of routes (or the weight of routes) between the $SU_s$ and $SU_d$ will be the same. As a result, Route 3 may be selected as the communication route between $SU_s$ and $SU_d$.

The routing criteria that are employed by CRNs have neglected at least one of the above-mentioned key factors when calculating the route weight.

In this paper, we propose a novel routing criterion, which is called the stability probability of communication between the source node and the destination node (SPC_SD), with the aim being to consider all of the mentioned key factors in the route-weight calculation.

To cover the channel diversity, we model CRN as a multigraph, where each vertex shows one SU and each edge a channel between two neighboring SUs. In this multigraph, the weight of each edge is determined based on the behavior of PU senders and the protection of PU receivers. SPC_SD precisely calculates the stability probability of communication between two SUs in the CRN using the obtained model and exploiting the internal backup routes. The performance evaluation is conducted using a NS2 simulator; the results show that SPC_SD can obtain a better packet delivery ratio than conventional routing criteria.

The rest of the paper is organized as follows. Section 2 discusses related work. Section 3 describes the network model and details of the SPC_SD definition. In Section 4, evaluation results of SPC_SD are shown, and the conclusion is given in Section 5.

## 2 | RELATED WORKS

Each routing method requires a criterion to find the optimal route between two nodes in the network. A routing criterion is a function that assigns a weight (or cost) to any given route [17]. In this section, we examine specifications of the criteria used in the CRN routing methods. We classify the proposed criteria into three categories: 1) delay-based routing criteria, 2) link stability-based routing criteria, and 3) multimetric-based routing criteria (combined routing criteria).

### 2.1 | Delay-based routing criteria

The routing methods presented in [18–20] are designed based on the routing methods provided for ad hoc networks. The criteria used in these methods have a combined queuing delay, back-off delay, and switching delay to calculate the route weight, as well as ignored PUs.[3)]

## 2.2 | Link stability-based routing criteria

In [21], the source node sends the route request (RREQ) message in a broadcast form to discover all of the possible routes to the destination node in the network. Any intermediate node that receives the RREQ message adds the address and a list of PUs that affects itself to the RREQ message, and then sends it to all of its neighbors. The destination node by the received RREQs selects the route with the greatest stability, and sends a unicast route reply (RREP) message. In fact, this method determines the route weight based on the behavior of PUs.

Paths that are far from each other are less influenced by the PU activity because one active PU would not be able to interrupt all of them simultaneously. Thus, the choice of nonclose routes can decrease the number of communication interruptions, and as a result, increase the communication stability. The idea in [22] is considered as a criterion for selecting two routes, one as the main route and the other as the auxiliary route.

In [23], each node periodically calculates the stability of its available channels based on the PU activity to reach its neighbors, and it adds channels that have the greatest steady-state probability to the neighbor table.

In this article, to realize route discovery, the source node sends the RREQ message to its neighbor. When an intermediate node receives the RREQ message, it first checks its routing table to find a path to the destination; if one exists, then it sends an RREP message. If there is no path to the destination, it checks its neighbor table, and if it is found that the destination is its neighbor, it updates its routing table and sends an RREP message; otherwise, the intermediate node sends an RREQ to its neighbors. The intermediate nodes and the source node add the route information to their routing table by receiving the RREP.

After the route discovery, the receiver node of the data packet refers to its routing table to select the node with the greatest steady-state probability of sending the data packet.

## 2.3 | Multimetric-based routing criteria (combined routing criteria)

The criterion proposed in [24] was defined based on the resource consumption and route stability in order to reflect the quality of service of the SU's requirements as well as statistical activities of PUs in the route-cost calculation.

[3)]The behavior of PU senders and protection of PU receivers are the most basic challenges in the CRN routing.

Two criteria are defined in [25]. These criteria are a combination of the availability probability of bandwidth, the variance of the number of bits sent on a link, specifications of the spectrum propagation, the protection of PU receivers, and spectrum-sensing considerations.

The combination of the route delay and remaining energy in the node is employed as a criterion in [26]. In this criterion, the route delay obtained by the criterion is provided in [19]. Also in [27], the route cost is obtained based on the availability probability of channels, and the remaining energy in the nodes constitute the route.

The criterion used in [28] is a combination of the link delay, link data rate, and hop count of the route. In this criterion, the link delay is obtained from the sum of the transmission delay, back-off delay, queuing delay, and switching delay, and the link data rate is specified based on the activity of PU senders. Also in [29], the statistical activities of PUs, switching delay, and the propagation delay were considered to select the route.

The routing method proposed in [30] finds all of the possible routes between the source node and destination node based on the channel diversity and route diversity. This method considers as the main route the route with the least number of hops, and other routes as the auxiliary routes. In fact, the criterion employed in this method is the number of route hops, while the channel diversity and route diversity are employed only in the route-discovery process. In addition, the route cost in [31] was determined only based on the number of channels that exist among neighboring nodes (channel diversity).

Basak and others combined the routing with the power-allocation strategy [32]. In this paper, the routing criterion is defined based on the interference to PU receivers and the CRN lifetime. In this study, the mode of SUs for spectrum access is not considered opportunistic. In [33], this group added to the study in [32] the opportunistic mode of spectrum access for SUs.

The routing criterion presented in [34] estimates the route weight based on the queue length of SUs, the contact degree of SUs, and the channel availability probability in order to guarantee reliable communication between the source node and destination node. In this criterion, the contact degree specifies the probability of communication such that two users can communicate with each other without interfering with PUs, and the channel availability probability is determined based on the activities of PUs in CRNs.

# 3 | PROPOSED ROUTING CRITERION

As shown in Section 2, the existing routing criteria that are employed to calculate the route weight have ignored at least one of the key factors mentioned in Section 1.[4)] Hence, in this section, we designed a novel routing criterion named SPC_SD, which considers all of the key factors. The important variables used in the discussion are summarized in Table 1.

We considered the following assumptions for the modeling of CRNs.

The spectrum used in CRNs is organized in $N$ separate bands ($N$ nonoverlapping channels) with similar properties. All SU nodes are assumed to use a common control channel (CCC) for spectrum access, which is always available. The SUs are equipped with $N+1$ radio interfaces to access channels (one for CCC and $N$ for the data channels). The SUs have different transmission regions, and their connections are considered in a full-duplex manner. The number and location of PU senders and the channel used by PU senders are known, while the number and location of PU receivers are not clear. The transmission region radius ($R_{\mathrm{PU}}$) and activity probability ($P_{\mathrm{PU}}$) of the PU senders are considered differently, whereas the average duration of their activity is considered identical.

We modeled CRN in the form of a weighted multigraph:

$$\mathrm{G} = (\mathrm{V}, \mathrm{E}) \tag{1}$$

where $v_k \in \mathrm{V}$ is the $k$th SU node ($\mathrm{SU}_K$), and $e^{c}_{i,j} \in \mathrm{E}$ represents the $c$th channel between $v_i$ and $v_j$ ($1 \geq c \leq N$). The expression "$v_i$ and $v_j$" represents two neighboring SUs.

**TABLE 1** List of Symbols used in the paper

| Symbols | Description |
|---|---|
| $N$ | Number of available channels |
| PUS | Set of primary users (PUs) senders that act on the $c$th channel |
| $R_{\mathrm{PU}}$ | Transfer region radius of PU |
| $P_{\mathrm{PU}}$ | Activity probability of PU |
| $R_v$ | Transfer region radius of SU |
| $v_i$ and $v_j$ | Two neighboring SUs |
| $e^c_{i,j}$ | $c$th channel between $v_i$ and $v_j$ |
| $\mathrm{IS}^c_{i,j}$ | Interference set related to $v_i$ and $v_j$ on the $c$th channel |
| $p^c_{i,j}$ | Stability probability of $e^c_{i,j}$ |
| $p^l_{i,j}$ | Link-stability probability between $v_i$ and $v_j$ |
| $P(R_{\mathrm{S,D}})$ | Route-stability probability between $v_{\mathrm{S}}$ and $v_{\mathrm{D}}$ |
| $P\left(\bigcap_{i=1}^{r} R^i_{\mathrm{S,D}}\right)$ | Stability probability of multiroute between $v_{\mathrm{S}}$ and $v_{\mathrm{D}}$ simultaneously |
| $P\left(\bigcup_{i=1}^{r} R^i_{\mathrm{S,D}}\right)$ | Stability probability of communication between $v_{\mathrm{S}}$ and $v_{\mathrm{D}}$ |

[4)]In practice, an unreal estimation of the route weight decreases the end-to-end performance of the network.

In this graph, the edge weight specifies the stability probability of $e^c_{i,j}$, so definition 3 determines how it should be calculated (see Figure 2).

Below, we explain some definitions that are employed when designing the proposed routing criterion.

**Definition 1** ($\mathrm{IS}^c_k$): a set of PU senders that can prevent the transfer of the $k$th SU node ($v_k$) on the c channel called $\mathrm{IS}^c_k$, which is calculated by (2).

$$\mathrm{IS}^c_k = \{\mathrm{PU}_1 \in \mathrm{PUS} \mid \sqrt{(x_{v_k} - x_{\mathrm{PU}_1})^2 + (y_{v_k} - y_{\mathrm{PU}_1})^2} < R_{v_k} + R_{\mathrm{PU}_1}\} \tag{2}$$

where PUS is a set of PU senders that act on the $c$ channel, and $\sqrt{}$ is the Euclidian distance $v_k$ from $\mathrm{PU}_1$, $R_{v_k}$ and $R_{\mathrm{PU}_1}$ specify the transfer region radius, $v_k$ and $\mathrm{PU}_1$.

**Definition 2** ($\mathrm{IS}^c_{i,j}$): a set of PU senders that can prevent data transfer on $e^c_{i,j}$ is called $\mathrm{IS}^c_{i,j}$, which is obtained using (3).

$$\mathrm{IS}^c_{i,j} = \mathrm{IS}^c_i \cup \mathrm{IS}^c_j, \tag{3}$$

$\mathrm{IS}^c_i$ and $\mathrm{IS}^c_j$ are calculated using (2).

In practice, when a PU belonging to $\mathrm{IS}^c_{i,j}$ is activated, $v_i$ and $v_j$ do not use the $c$ channel. Consequently, $v_i$ and $v_j$ do not cause trouble for PUs receivers on the $c$ channel (the protection of PU receivers).

**Definition 3** (the stability probability of $e^c_{i,j}$): $p^c_{i,j}$ specifies the probability that $e^c_{i,j}$ is not influenced by the activity of PU senders belonging to $\mathrm{IS}^c_{i,j}$. The manner in which $p^c_{i,j}$ is obtained is shown in (4).

$$p(e^c_{i,j}) = p^c_{i,j} = \prod_{\mathrm{PU_s} \in \mathrm{IS}^c_{i,j}} (1 - P_{\mathrm{PU_s}}), \tag{4}$$

$P_{\mathrm{PU_s}}$ specifies the activity probability of the $\mathrm{PU_s}$ senders, and $\mathrm{IS}^c_{i,j}$ is obtained using (3). SUs are able to estimate $\mathrm{P}_{\mathrm{PU_s}}$ based on the historical use of the channel by $\mathrm{PU_s}$.

**Definition 4** (link-stability probability between $v_i$ and $v_j$): The link between $v_i$ and $v_j$ will be stable if there exists at least one free channel between them. With regard to the independence of the stability probability of channels

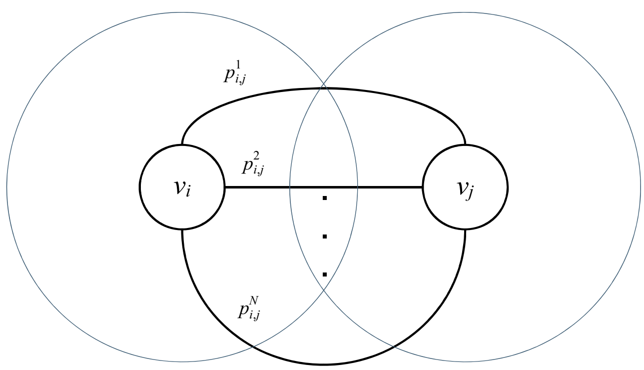


**FIGURE 2** Part of graph G

relative to each other, the link-stability probability between $v_i$ and $v_j$ ($p^{\ell}_{i,j}$) is calculated using (5).

$$p^{\ell}_{i,j} = p(\ell_{i,j}) = 1 - \prod_{c=1}^{N}(1 - p^{c}_{i,j}), \tag{5}$$

$p^{c}_{i,j}$ can be calculated using (4). Therefore, by inserting (4) in (5):

$$p(\ell_{i,j}) = 1 - \prod_{c=1}^{N}\left(1 - \prod_{\mathrm{PU_s} \in \mathrm{IS}^{c}_{i,j}}(1 - P_{\mathrm{PU_s}})\right). \tag{6}$$

**Definition 5** (route-stability probability between two SUs): In general, the route between the source SU node (S) and destination SU node (D) is a set with the member $h$, which can be given as (7).

$$R_{\mathrm{S,D}} = \{\ell_{\mathrm{S},i_1}, \ell_{i_1,i_2}, \ldots, \ell_{i_{h-1},\mathrm{D}}\}. \tag{7}$$

Based on (7), the stability probability of $R_{\mathrm{S,D}}$ can be expressed as (8).

$$\begin{aligned} P(R_{\mathrm{S,D}}) &= P(\ell_{\mathrm{S},i_1} \cap \ell_{i_1,i_2} \cap \cdots \cap \ell_{i_{h-1},\mathrm{D}}) \\ &= 1 - [P(\bar{\ell}_{\mathrm{S},i_1} \cup \bar{\ell}_{i_1,i_2} \cup \cdots \cup \bar{\ell}_{i_{h-1},\mathrm{D}})] \\ &= 1 - [P(\bar{\ell}_{\mathrm{S},i_1}) + P(\bar{\ell}_{i_1,i_2}) + \cdots + P(\bar{\ell}_{i_{h-1},\mathrm{D}}) \\ &\quad - P(\bar{\ell}_{\mathrm{S},i_1} \cap \bar{\ell}_{i_1,i_2}) - \cdots - P(\bar{\ell}_{i_{h-2},i_{h-1}} \cap \bar{\ell}_{i_{h-1},\mathrm{D}}) \\ &\quad + P(\bar{\ell}_{\mathrm{S},i_1} \cap \bar{\ell}_{i_1,i_2} \cap \bar{\ell}_{i_2,i_3}) + \cdots \\ &\quad + P(\bar{\ell}_{i_{h-3},i_{h-2}} \cap \bar{\ell}_{i_{h-2},i_{h-1}} \cap \bar{\ell}_{i_{h-1},\mathrm{D}}) + \cdots \\ &\quad \pm P(\bar{\ell}_{\mathrm{S},i_1} \cap \bar{\ell}_{i_1,i_2} \cap \cdots \cap \bar{\ell}_{i_{h-1},\mathrm{D}})], \end{aligned} \tag{8}$$

$$P(\bar{\ell}_{i,j}) = 1 - P(\ell_{i,j}). \tag{9}$$

By inserting (6) in (9),

$$P(\bar{\ell}_{i,j}) = \prod_{c=1}^{N}\left(1 - \prod_{\mathrm{PU_s} \in \mathrm{IS}^{c}_{i,j}}(1 - P_{\mathrm{PU_s}})\right), \tag{10}$$

$$\begin{aligned} &P(\bar{\ell}_{j_1,j_2} \cap \bar{\ell}_{j_2,j_3} \cap \cdots \cap \bar{\ell}_{j_{m-1},j_m}) \\ &= \prod_{c=1}^{N} P(\bar{e}^{c}_{j_1,j_2} \cap \bar{e}^{c}_{j_2,j_3} \cap \cdots \cap \bar{e}^{c}_{j_{m-1},j_m}), \end{aligned} \tag{11}$$

$$\begin{aligned} &P(\bar{e}^{c}_{j_1,j_2} \cap \bar{e}^{c}_{j_2,j_3} \cap \cdots \cap \bar{e}^{c}_{j_{m-1},j_m}) \\ &= 1 - [P(e^{c}_{j_1,j_2} \cup e^{c}_{j_2,j_3} \cup \cdots \cup e^{c}_{j_{m-1},j_m})] \\ &= 1 - [P(e^{c}_{j_1,j_2}) + P(e^{c}_{j_2,j_3}) + \cdots + P(e^{c}_{j_{m-1},j_m}) \\ &\quad - P(e^{c}_{j_1,j_2} \cap e^{c}_{j_2,j_3}) - \cdots - P(e^{c}_{j_{m-2},j_{m-1}} \cap e^{c}_{j_{m-1},j_m}) \\ &\quad + P(e^{c}_{j_1,j_2} \cap e^{c}_{j_2,j_3} \cap e^{c}_{j_3,j_4}) + \cdots \\ &\quad + P(e^{c}_{j_{m-3},j_{m-2}} \cap e^{c}_{j_{m-2},j_{m-1}} \cap e^{c}_{j_{m-1},j_m}) \cdots \\ &\quad \pm P(e^{c}_{j_1,j_2} \cap e^{c}_{j_2,j_3} \cdots \cap e^{c}_{j_{m-1},j_m})], \end{aligned} \tag{12}$$

$$\begin{aligned} &P(e^{c}_{k_1,k_2} \cap e^{c}_{k_2,k_3} \cap \cdots \cap e^{c}_{k_{m-1},k_m}) \\ &= \prod_{\mathrm{PU_s} \in \left\{\mathrm{IS}^{c}_{k_1,k_2} \cup \mathrm{IS}^{c}_{k_2,k_3} \cup \cdots \cup \mathrm{IS}^{c}_{k_{m-1},k_m}\right\}} (1 - \mathrm{P}_{\mathrm{PU_s}}). \end{aligned} \tag{13}$$

The route-stability probability is obtained by inserting (4) and (13) into (12), (12) into (11), and (11) and (10) into (8).

In fact, (8) calculates the route-stability probability between node S and node D based on the behavior of PU senders, the protection of PU receivers, and the channel diversity.

**Definition 6** (stability probability of multiroute between two SUs simultaneously): If $R^{i}_{\mathrm{S,D}}$ and $R^{j}_{\mathrm{S,D}}$ specify the routes between S and D, the stability of $R^{i}_{\mathrm{S,D}}$ and $R^{j}_{\mathrm{S,D}}$ simultaneously means that the hops forming $R^{i}_{\mathrm{S,D}}$ and $R^{j}_{\mathrm{S,D}}$ must be stable. Therefore, the stability of $R^{i}_{\mathrm{S,D}}$ and $R^{j}_{\mathrm{S,D}}$ simultaneously could be defined as (14).

$$R^{i}_{\mathrm{S,D}} \cap R^{j}_{\mathrm{S,D}} = \cap R^{i,j}_{\mathrm{S,D}} = \{\ell | \ell \in R^{i}_{\mathrm{S,D}} \vee \ell \in R^{j}_{\mathrm{S,D}}\}. \tag{14}$$

With respect to (14), (15) shows the stability probability of $R^{i}_{\mathrm{S,D}}$ and $R^{j}_{\mathrm{S,D}}$ simultaneously.

$$P(\cap R^{i,j}_{\mathrm{S,D}}) = P\left(\bigcap_{\ell \in \cap R^{i,j}_{\mathrm{S,D}}} \ell\right). \tag{15}$$

Similarly, if $\{R^{1}_{\mathrm{S,D}}, R^{2}_{\mathrm{S,D}}, \ldots, R^{r}_{\mathrm{S,D}}\}$ shows the routes between node S and node D, their stability is simultaneously expressed as (16).

$$\begin{aligned} &R^{1}_{\mathrm{S,D}} \cap R^{2}_{\mathrm{S,D}} \cap \cdots \cap R^{1,2,\ldots,r}_{\mathrm{S,D}} = \bigcap_{i=1}^{r} R^{i}_{\mathrm{S,D}} \\ &\{\ell | \ell \in R^{1}_{\mathrm{S,D}} \vee \ell \in R^{2}_{\mathrm{S,D}} \vee \cdots \vee \ell \in R^{r}_{\mathrm{S,D}}\}. \end{aligned} \tag{16}$$

With respect to (16), (17) shows the stability probability of $\{R^{1}_{\mathrm{S,D}}, R^{2}_{\mathrm{S,D}}, \ldots, R^{r}_{\mathrm{S,D}}\}$ simultaneously.

$$P\left(\bigcap_{i=1}^{r} R^{i}_{\mathrm{S,D}}\right) = P\left(\bigcap_{\ell \in \cap R^{1,2,\ldots,r}_{\mathrm{S,D}}} \ell\right). \tag{17}$$

In practice, (17) can be calculated using (8) by obtaining the set of $\bigcap_{i=1}^{r} R^{i}_{\mathrm{S,D}}$.

**Definition 7** (internal backup route): If $\{R^{1}_{\mathrm{S,D}}, R^{2}_{\mathrm{S,D}}, \ldots, R^{r}_{\mathrm{S,D}}\}$ shows the routes between S and D, which are common in the first hop, $R^{i}_{\mathrm{S,D}}$ $(1 \le i \le r)$ is one internal backup route for routes belonging to $\{\{R^{1}_{\mathrm{S,D}}, R^{2}_{\mathrm{S,D}}, \ldots, R^{r}_{\mathrm{S,D}}\} - R^{i}_{\mathrm{S,D}}\}$.

**Definition of proposed routing criterion** (the stability probability of communication between the two SUs): If $\{R^{1}_{\mathrm{S,D}}, R^{2}_{\mathrm{S,D}}, \ldots, R^{r}_{\mathrm{S,D}}\}$ shows the routes between S and D, which are common in the first hop, the stability probability of communication between S and D using this set, which is called SPC_SD, can be calculated using (18).

$$
\begin{aligned}
P(R^1_{\mathrm{S,D}} \cup R^2_{\mathrm{S,D}} \cup \cdots \cup R^r_{\mathrm{S,D}}) &= P(\cup R^{1,2,\ldots,r}_{\mathrm{S,D}}) = P\left(\bigcup_{i=1}^{r} R^i_{\mathrm{S,D}}\right) \\
&= P(R^1_{\mathrm{S,D}}) + P(R^2_{\mathrm{S,D}}) + \cdots + P(R^r_{\mathrm{S,D}}) \\
&\quad - P(\cap R^{1,2}_{\mathrm{S,D}}) - P(\cap R^{1,3}_{\mathrm{S,D}}) - \cdots - P(\cap R^{r-1,r}_{\mathrm{S,D}}) \\
&\quad + P(\cap R^{1,2,3}_{\mathrm{S,D}}) + P(\cap R^{1,2,4}_{\mathrm{S,D}}) + \cdots + P(\cap R^{r-2,r-1,r}_{\mathrm{S,D}}) \\
&\quad \ldots \\
&\quad \pm P(\cap R^{1,2,\ldots,r}_{\mathrm{S,D}}) \\
&= \sum_{i=1}^{r} (-1)^{i+1} \sum P\left(\cap R_{\mathrm{S,D}}^{\binom{1,2,\ldots,r}{i}}\right).
\end{aligned}
\tag{18}
$$

In (18), $\binom{1,2,\ldots,r}{i}$ specifies the $i$th subsets of $\{1,2,\ldots,r\}$, $P(\cap R^{-,-,\ldots,-}_{\mathrm{S,D}})$ is calculated by (17), and $P(R^i_{\mathrm{S,D}})$ is calculated by (8).

In practice, SPC_SD obtains the stability probability of communication between node S and node D based on the behavior of PU senders and the protection of PU receivers, channel diversity, and internal backup routes.

## 4 | EVALUATION OF SPC_SD

The routing protocol based on SPC_SD (RP_SPC_SD) is implemented in the ns-2 simulator. In RP_SPC_SD, the source node broadcasts the RREQ message to discover all of the possible routes to the destination node in the network. If the address of the intermediate node receiving the RREQ does not exist in the RREQ, it adds the address and the list of PUs that affects itself to the RREQ, and sends the RREQ to all of its neighbors. When the destination node receives an RREQ message, it forms the RREP message using the information contained in the RREQ. Then, the destination node sends the RREP to the node that has received the RREQ from it. When an intermediate node receives the RREP message, it sends RREP to the next node using the list contained in RREP. The source node used by the received RREPs selects the route with the greatest SPC_SD in order to send the data packet to the destination.

To simulate the CRN, a square space is considered with a side of 2,000 m divided into 25 square cells with sides of 400 m. Then, the PU senders are placed at the center of the cells so that odd-numbered PUs are active on channel 0, and even-numbered PUs are active on channel 1 based on the ON-OFF exponential model [35]. The number and location of the SUs are specified with regard to the defined configurations for evaluation (Figures 3–6). The parameters that are related to the performed simulations are briefly shown in Table 2. This article focuses on the routing criterion; hence, we assumed that the identification of the PUs is performed correctly in the physical layer.

RP_SPC_SD was compared with the cognitive ad hoc on-demand distance vector (CAODV) protocol [36].

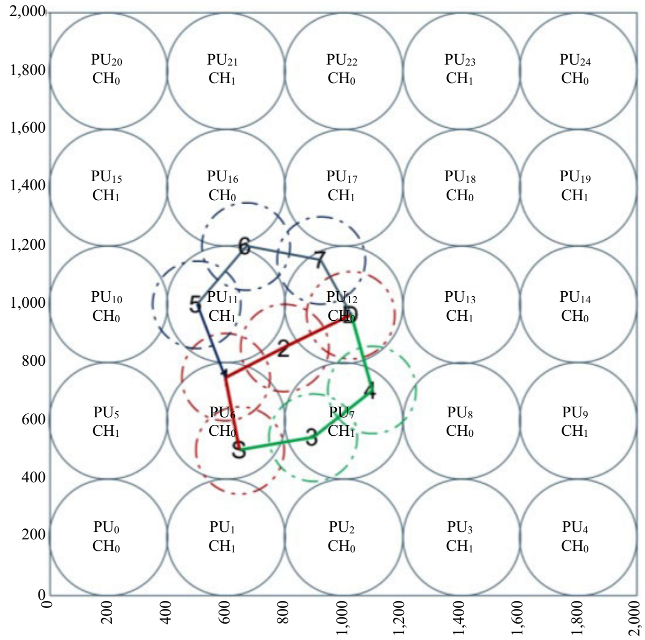


**FIGURE 3** Configuration1, DIS_S_D = 3

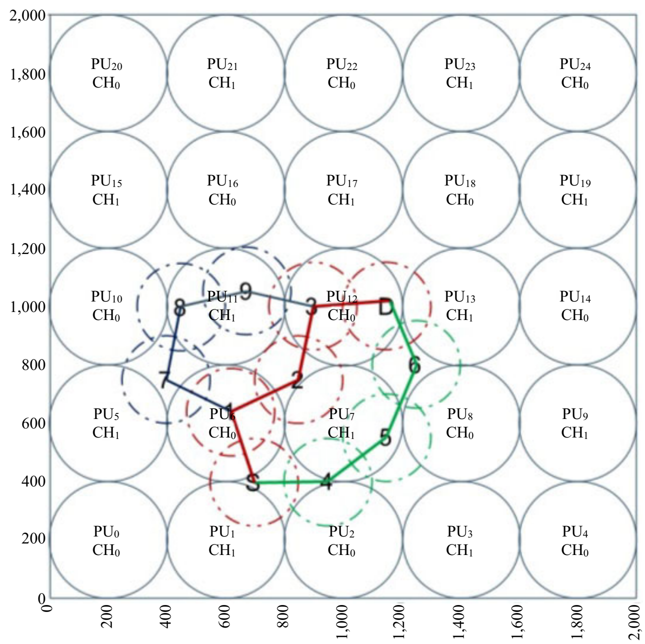


**FIGURE 4** Configuration2, DIS_S_D = 4

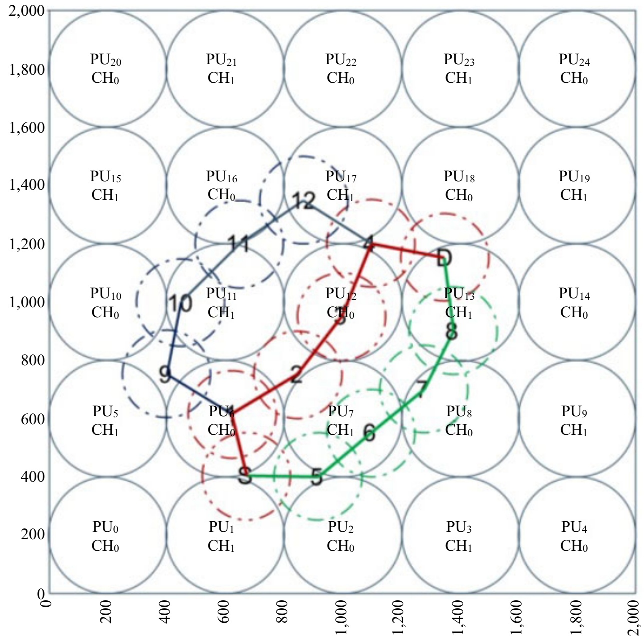


**FIGURE 5** Configuration3, DIS_S_D = 5

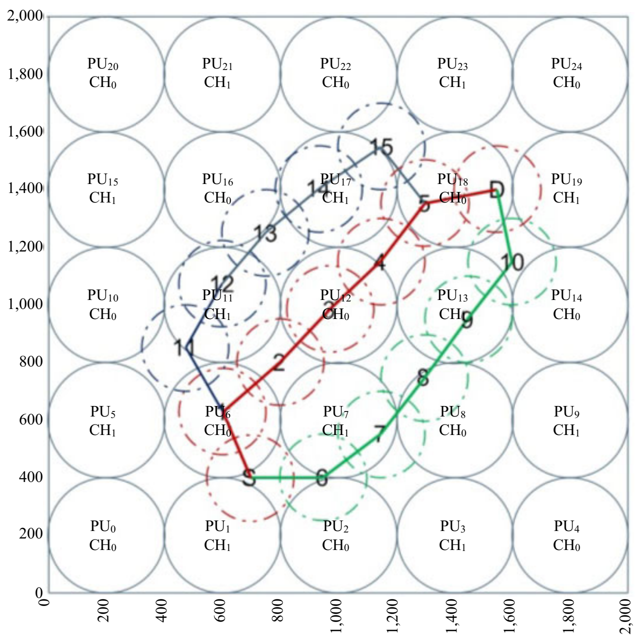


**FIGURE 6** Configuration4, DIS_S_D = 6

CAODV is an improved version of the AODV protocol, which tries to prevent the SU activity during the activity period of PU. CAODV calculates the route weight between two SU nodes based on the number of hops without considering the channel diversity and internal backup routes. The packet delivery ratio (PDR) to the destination node is employed as the evaluation criterion.

The purpose of this article is to show the effect of the channel diversity and the internal backup routes in the routing process, as well as to show the effect of ignoring them. Thus, we designed the four configurations to compare RP_SPC_SD with the CAODV protocol, for which the details are shown in Figures 3–6.

In the designed configurations, two channels and two routes with the same number of hops (green route and red route) were considered to illustrate the effect of channel diversity and the internal backup routes, respectively. The red route has an internal backup route, whereas the green route does not have an internal backup route.

In practice, an increase in the distance between the source node and destination node (DIS_S_D) as well as the activity probability of PU senders (A_PR_PU) decrease the stability probability of routes in CRNs. Thus, we defined

**TABLE 2** Parameters used in the simulations

| Parameter name | Value |
|---|---|
| Simulator software | ns-2, version 2.31 |
| Simulation area | 2,000 m × 2,000 m |
| Simulation time | 50 s |
| Radio propagation model | Two-ray ground |
| Interface queue type | DropTail/PriQueue |
| MAC layer | IEEE 802.11 |
| Antenna model | Omni antenna |
| Number of channels | 2 |
| Data traffic model | CBR over UDP |
| Data packet size | 1,000 bytes |
| Data packet interval | 0.0625 s |
| Number of SUs | 9, 11, 14, 17 |
| Transmission range radius of SU | 150 m |
| Number of PU | 25 |
| Transmission range radius of PU | 200 m |
| PU activity checking interval | 0.2 s |
| Duration of PU activity | 1 s |

**TABLE 3** Scenario defined for comparison of RP_SPC_SD with CAODV protocol

| Scenario | Configuration | A_PR_PU (%) |
|---|---|---|
| 1 | 1 | 20–70 |
| 2 | 2 | 20–70 |
| 3 | 3 | 20–70 |
| 4 | 4 | 20–70 |
| 5 | 1, 2, 3, 4 | 20 |
| 6 | 1, 2, 3, 4 | 30 |
| 7 | 1, 2, 3, 4 | 40 |
| 8 | 1, 2, 3, 4 | 50 |
| 9 | 1, 2, 3, 4 | 60 |
| 10 | 1, 2, 3, 4 | 70 |

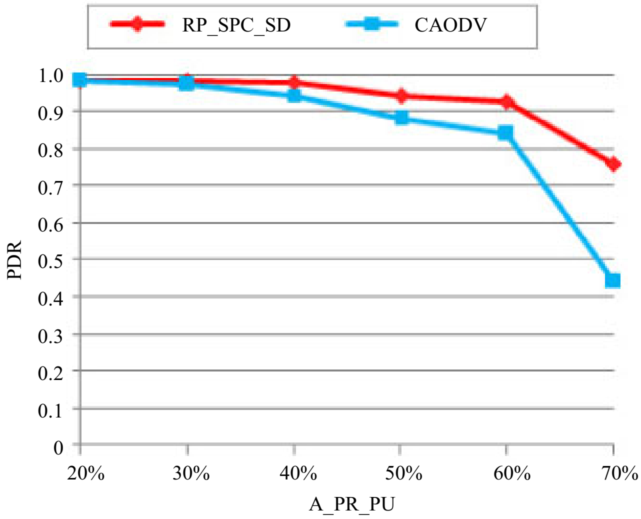


**FIGURE 7** Simulation results of scenario 1

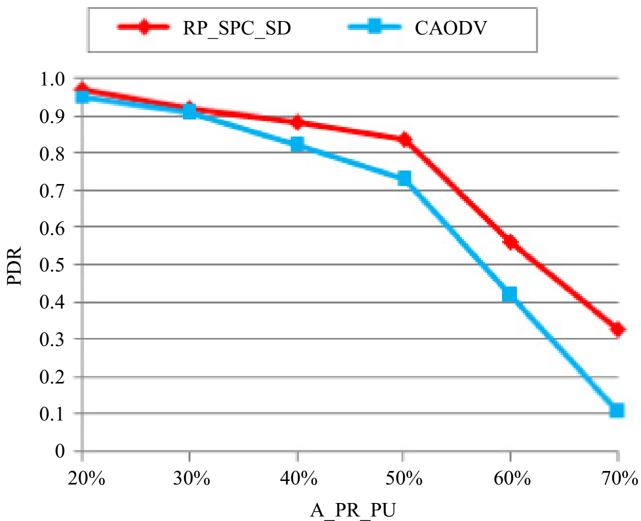


**FIGURE 8** Simulation results of scenario 2

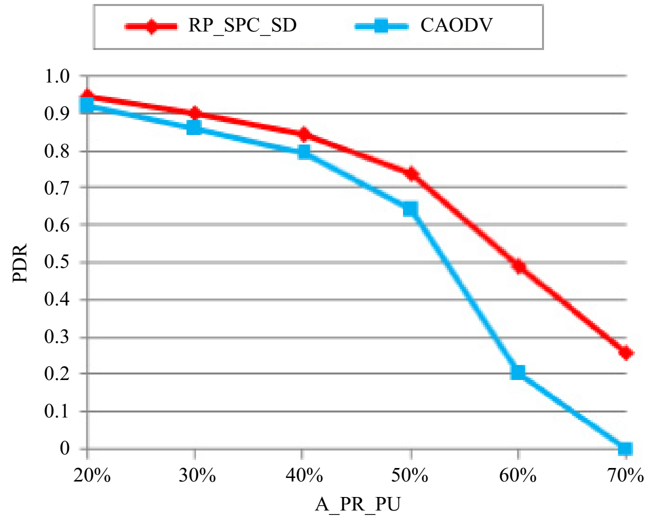


**FIGURE 9** Simulation results of scenario 3

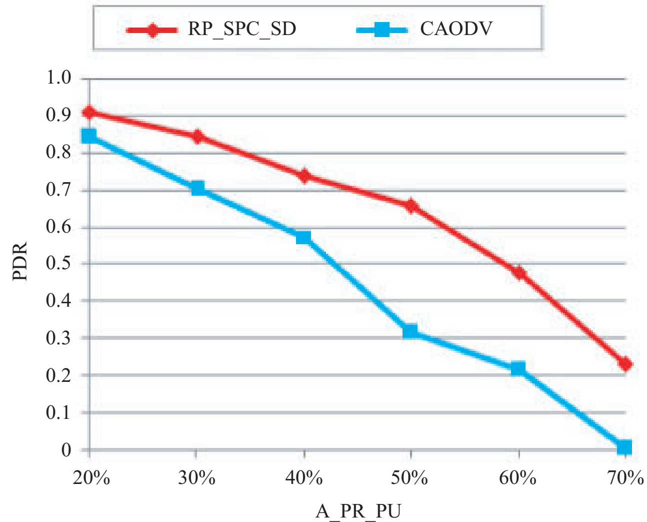


**FIGURE 10** Simulation results of scenario 4

10 scenarios based on DIS_S_D and A_PR_PU in order to compare RP_SPC_SD with the CAODV protocol, for which the details are shown in Table 3.

Figures 7–10 and Tables 4–9, respectively, depict the simulation results obtained for scenarios 1–10 based on the parameters mentioned in Table 2. They illustrate the behavior of the two protocols in terms of the PDR.

By observing Figures 7–10 separately, it can be seen that for a constant DIS_S_D, as A_PR_PU increases, RP_SPC_SD exhibits a very good PDR compared with the CAODV protocol.

However, by surveying Tables 4–9 separately, it can be concluded that if A_PR_PU is constant, an increase in DIS_S_D results in a significant increase in the PDR related to RP_ SPC_SD when compared with the PDR related to the CAODV protocol.

**TABLE 4** Simulation results of scenario 5

| DIS_S_D | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| PDR | | | | |
| RP_SPC_SD | 0.98493 | 0.96871 | 0.94697 | 0.91083 |
| CAODV | 0.98232 | 0.94836 | 0.92128 | 0.84416 |

The behaviors described in Figures 7–10 and Tables 4–9 reflect the fact that in conditions where there is an increasing instability of routes, the application of RP_SPC_SD by exploiting available opportunities in CRN is able to realize a much better efficiency than the CAODV protocol.

**TABLE 5** Simulation results of scenario 6

| DIS_S_D | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| PDR | | | | |
| RP_SPC_SD | 0.98477 | 0.91824 | 0.90047 | 0.84444 |
| CAODV | 0.97368 | 0.90404 | 0.85998 | 0.70566 |

**TABLE 6** Simulation results of scenario 7

| DIS_S_D | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| PDR | | | | |
| RP_SPC_SD | 0.97870 | 0.88020 | 0.84450 | 0.73955 |
| CAODV | 0.94373 | 0.81944 | 0.79449 | 0.57561 |

**TABLE 7** Simulation results of scenario 8

| DIS_S_D | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| PDR | | | | |
| RP_SPC_SD | 0.94022 | 0.83709 | 0.74120 | 0.65880 |
| CAODV | 0.87841 | 0.72704 | 0.64321 | 0.31691 |

**TABLE 8** Simulation results of scenario 9

| DIS_S_D | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| PDR | | | | |
| RP_SPC_SD | 0.92528 | 0.56039 | 0.49178 | 0.47766 |
| CAODV | 0.83862 | 0.41770 | 0.20275 | 0.21571 |

**TABLE 9** Simulation results of scenario 10

| DIS_S_D | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| PDR | | | | |
| RP_SPC_SD | 0.75954 | 0.32656 | 0.25940 | 0.22970 |
| CAODV | 0.44040 | 0.10646 | 0.00376 | 0.00499 |

As a general conclusion, the results shown above prove that RP_SPC_SD can improve the end-to-end performance significantly, especially in circumstances for which the stability of routes is decreased in CRNs.

## 5 | CONCLUSION

It is difficult to define the routing criterion in CRNs because it is affected by various factors. This paper introduces a novel routing criterion called SPC_SD for CRNs. The proposed SPC_SD definition considers the available opportunities in CRNs, such as the channel diversity and internal backup routes, as well as the behavior of PU senders and the protection of PU receivers. The SPC_SD-based routing protocol was compared with the CAODV protocol, which does not consider the channel diversity and internal backup routes. The results of comparisons show that the proposed SPC_SD can improve the end-to-end performance significantly. The SPC_SD specification and results of simulations show that SPC_SD may be suitable for different types of CRNs.

In this paper, SPC_SD was designed based on CRNs in which operational channels have similar attributes. Therefore, in future, our aim is to design a routing criterion for which there is no assumption of homogeneous operational channels.

## ORCID

*Ahmad Yousofi* http://orcid.org/0000-0003-3108-5556

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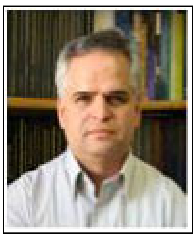
## AUTHOR BIOGRAPHIES

**Ahmad Yousofi** received his BSc degree from the Islamic Azad University, Qazvin branch, Iran, and his MSc degree from the Amirkabir University of Technology (Tehran Polytechnic), Iran, both in the field of computer engineering in 2002 and 2007, respectively. Currently, he is pursuing his PhD degree in the field of computer engineering at the Islamic Azad University, Science and Research Branch, Tehran, Iran. Since 2007, he has been a faculty member of the Computer Engineering Department, Islamic Azad University, Naein branch, Iran. His research interests are wireless networks, cognitive radio networks, and parallel processing.



**Masoud Sabaei** received his BSc degree from Esfahan University of Technology, Iran, and his MSc and PhD degrees from the Amirkabir University of Technology (Tehran Polytechnic), Iran, all in the field of computer engineering, in 1992, 1995, and 2000, respectively. Since 2002, He has been a professor in the Computer Engineering Department, Amirkabir University of Technology. His research interests are software-defined networking, the Internet of Things, wireless networks, and telecommunication network management.

**Mehdi Hosseinzadeh** received his BSc in computer hardware engineering from the Islamic Azad University, Dezful branch, Iran, in 2003. He also received the MSc and PhD degrees in computer system architecture from the Science and Research Branch, Islamic Azad University, Tehran, Iran, in 2005 and 2008, respectively. He is currently an Associate Professor at the Iran University of Medical Sciences, Tehran, Iran. His research interests are information technology, data mining, big data analytics, E-commerce, E-marketing, and social networks.